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Feasibility Analysis of Importing PHA instead of PE in Singapore

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Abstract: This article presents a comprehensive examination of Singapore's thriving service and transportation sectors, with a particular focus on the increasing demand for packaging and disposable goods. The subsequent heavy reliance on polyethylene (PE) is emphasized. Subsequently, the article delves into the ecological consequences associated with the widespread use of PE in Singapore. This encompasses considerations such as ecological space occupancy, plastic pollution, and greenhouse gas emissions. In response to these pressing challenges, the article suggests practical solutions. With a strong emphasis on environmental concerns, the article promotes the adoption of polyhydroxyalkanoates (PHA) as a feasible and eco-friendly alternative to the environmentally detrimental PE. This proposal is juxtaposed with a comprehensive comparative analysis of other renewable materials like polylactic acid (PLA) and PHA, critically evaluating their innovative potential and inherent limitations. To ensure the successful implementation of the proposed solutions, the article presents a diverse range of resource management strategies. Additionally, the article outlines a clear pathway for transitioning and upgrading Singapore's existing polyethylene products. It offers well-founded explanations and recommendations for advancing industries while comparing the feasibility, financial aspects, transformation challenges, and strategies between the LDPE and PHA sectors. The article culminates in a meticulous simulation that calculates the financial requirements for a complete shift from PE to PHA in Singapore by 2021, along with the subsequent cost implications for the packaging industry. These rigorous analyses and calculations provide precise quantitative guidance, aiding policymakers, entrepreneurs, and decision-makers in making well-informed decisions for transformative initiatives.

Keywords: PE, PHA, Singapore, Environmental Challenges, Replacement, Food Packaging Industry, Simulation Analysis.

1. Primary Polymer Material Dependency in Singapore - PE

Singapore, a dynamic city-state despite its small size, boasts an advanced service sector and a prominent position in global trade. Its economic vitality is fueled by international trade, technological innovation, and services. However, due to its limited land and resources, Singapore finds itself heavily reliant on imports to overcome production constraints. This situation presents the nation with the intricate challenge of harmonizing economic growth with sustainability, especially as environmental concerns continue to gain momentum.

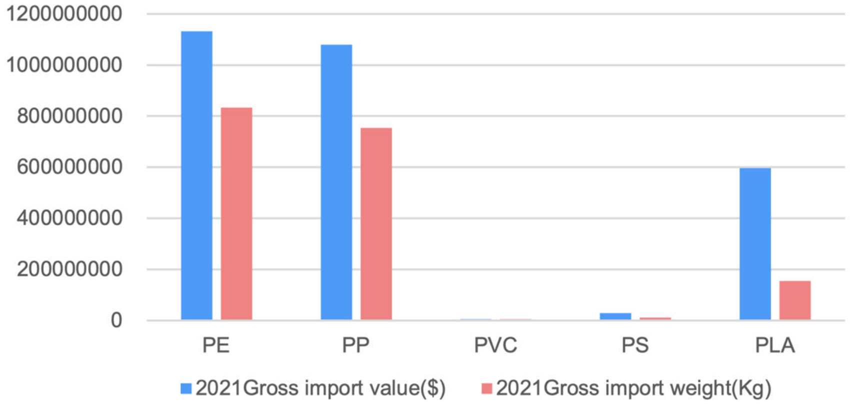

Figure 1. 2021 Primary Plastic Import Statistics in Singapore.

In recent years, the substantial import of various plastic materials underscores the pivotal role plastics play in propelling Singapore's economic expansion and modern industrialization. Polyethylene, polypropylene, polyvinyl chloride, and styrene are indispensable components across industries such as packaging, construction, electronics, and automotive. A meticulous examination of the United Nations Comtrade Database (https://comtradeplus.un.org/) reveals the prominence of polyethylene as a key imported plastic in Singapore, as depicted in Figure 1. Notably, the import of low-density polyethylene has demonstrated stability over the past three years, with demand consistently maintained at a robust level, as demonstrated in Figure 2.

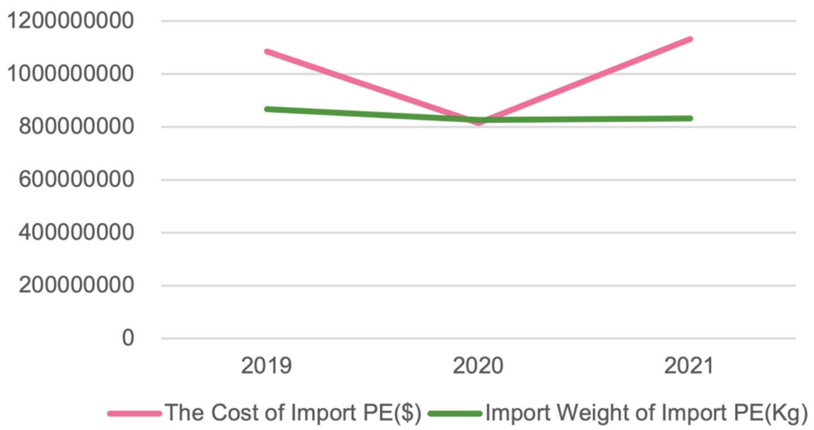

Figure 2. LDPE import data change table for three consecutive years.

Polyethylene (PE) serves a multitude of vital functions within Singapore's context, encompassing:

Packaging Industry: PE stands as a fundamental plastic in the packaging domain. Within Singapore, PE bags, films, and plastic bottles find extensive usage in packaging food, pharmaceuticals, and everyday essentials. Its attributes of lightness, durability, and remarkable transparency render it an optimal material choice for safeguarding products and extending their shelf life.

Construction Sector: PE assumes significant roles, notably in pipes and insulation materials. PE pipes are pivotal for conveying water, natural gas, sewage, and chemicals, given their resistance to corrosion and capacity to withstand pressure.

Medical Applications: In the realm of medical supplies, PE finds application in producing medical packaging, syringes, test tubes, and medical bags. Its non-toxic properties, corrosion resistance, and economical nature make it a prevalent choice in medical equipment and instruments.

Automotive Manufacturing: The automotive industry widely integrates PE products, incorporating them into interior components, seats, dashboards, and more. The inherent lightweight quality of PE contributes to the overall weight reduction of vehicles, thereby enhancing fuel efficiency.

Chemical Industry: Within the chemical sector, PE plays a pivotal role in crafting chemical containers, pipes, and an array of other components. It also finds utility within the industrial sphere for fabricating containers and storage tanks.

The versatile utility of PE within Singapore embraces various dimensions of daily existence, spanning packaging, construction, medical applications, and automotive uses. Nevertheless, suboptimal practices related to the production, processing, utilization, and recycling of high-polymer materials like PE have introduced an array of environmental challenges for Singapore.

2. Environmental Challenges Posed by PE in Singapore

As a synthetic high molecular polymer, polyethylene products are extremely resistant to degradation, and effective microorganisms or enzymes for degrading PE have not yet been discovered. Consequently, in natural conditions, the degradation of PE products takes decades or even longer, resulting in prohibitively high time costs. Meanwhile, within a confined space, the accumulation of plastic over extended periods can have detrimental effects on the local environment. Singapore, renowned as the "Garden City," is a biologically diverse habitat with tens of thousands of terrestrial and marine species inhabiting the nation. Non-degradable plastics encroach upon spaces vital for biological survival, significantly impacting the overall range of movement for various species.

Figure 3. Plastic Bottles on Sentosa Beach in Singapore

This obstruction hampers normal reproduction, behavioral activities, and may further imperil ecological system dynamics and stability, as illustrated in Figure 3. Given Singapore's limited geographical space, the issue of plastic waste control and management becomes an urgent priority. Plastics, due to their prolonged non-degradability or partial degradation into plastic fragments, present significant environmental threats that escalate over time. The prevalent presence of microplastics in recent years has raised an alarm for society and poses a hazard to drinking water safety. Singapore, as a water-scarce nation, greatly values its limited land and water resources. The potential threat of water contamination stemming from microplastics introduction is objectively severe and demands immediate attention.

The plastic production process also merits consideration. Industrial production in high-temperature and high-pressure conditions demands substantial and continuous energy input, rendering it energy-intensive. Currently, one of the major energy sources for industrial processes is coal combustion, releasing significant greenhouse gases like carbon dioxide and methane. This exacerbates global warming, contributing to issues such as glacier melting and rising sea levels. For Singapore, a coastal country, sea level height and climate stability are critical concerns that directly impact port transportation safety, tourism services, and overall public well-being. Taking all these factors into account, plastics, especially PE, present formidable challenges to environmental conservation in Singapore. The pursuit of more energy-efficient and environmentally friendly methodologies is an imperative trend. In response to the issues posed by PE in Singapore, we have opted to replace PE materials with PHA materials.

3. Choosing PHA as a Replacement for PE

3.1. Introduction to PHA and its Pros and Cons

Polyhydroxyalkanoates (PHA) are macromolecular biomaterials consisting of 100-3000 identical or different hydroxyl fatty acid monomers, most of which are 3-hydroxyl fatty acids with chain lengths of 3-14 carbon atoms, and side chains are highly variable aromatic or aliphatic groups. Found in microbial cells such as bacterial cells (similar to bacterial fat). It is the product of bacteria when growth conditions are unbalanced, and it is also a carbon source and energy storage substance in microorganisms. PHA research began in the 1920s and has gradually begun to be industrialized.

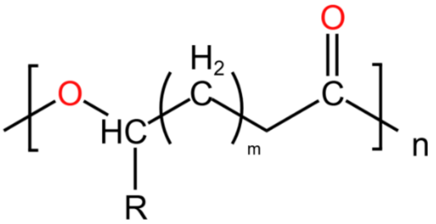

Figure 4. Schematic Representation of PHA Structure

There are many kinds of PHA, and according to research, there are more than 150 kinds of PHA monomer. According to the monomer chain length, PHA can be divided into two categories: one is a Short Chain PHA (SCL) with 3-5 carbon atom monomer chain length; The other is the Medium-Long Chain PHA (MCL) with 6-14 carbon monomer chain lengths. According to the types of monomers, PHA can be divided into homopolymers and copolymers. PHA has been developed to the fourth generation of products[1].

The molecular weight of PHA ranges from 1000 to 1000000, with a glass transition temperature of -60 °C to +60 °C and a melting point of +40 °C to 190 °C. Its barrier properties against water vapor and most gases in the air are similar to PET (polyethylene terephthalate). PHA possesses unique characteristics, including biodegradability, biocompatibility, and environmental friendliness. These exceptional properties give PHA numerous potential applications, leading to extensive research by scientists worldwide to develop processing methods and explore specific properties.

3.2. Comparison between PHA and LDPE

Table 1. Comparison of LDPE and PHA Properties[2]

	LDPE	PHA
Melting point/°C	110	145
Tensile strength/Mpa	12	30
Elongation rate/%	148	10
Degradation rate	-	fast
Oxygen barrier	poor	better
Water vapor barrier	better	good

In terms of physical properties (Table 1), both LDPE and PHA exhibit excellent flexibility, which is crucial for producing various packaging materials. They also possess considerable tensile strength and impact resistance, ensuring thorough protection of packaged products[3]. However, these two polymers show significant differences in terms of environmental performance. PE is a petroleum-based polymer that is non-biodegradable and can persist in the environment for hundreds to thousands of years. On the other hand, PHA is biodegradable and can be completely broken down by microorganisms in the environment within a few months to several years, depending on the specific type of PHA and environmental conditions[4].

LDPE and PHA share some common attributes in the packaging field. Their exceptional flexibility, tensile strength, and impact resistance make them suitable for a wide range of packaging applications, including food packaging, consumer goods packaging, and industrial packaging. Furthermore, both LDPE and PHA can be processed using similar techniques such as film extrusion, injection molding, and blow molding, facilitating the transition from LDPE to PHA within existing manufacturing systems[3].

The biodegradability of PHA positions it as a more environmentally friendly alternative to PE. While PE packaging contributes significantly to the global plastic waste problem, PHA packaging can be composted after use, reducing the need for waste disposal and landfilling. Additionally, PHA can be produced from renewable resources such as plant sugars or waste biomass, further enhancing its environmental performance[4].

3.3. Comparison between PHA and PLA

PHA's degradation method and rate surpass that of PLA. As indicated in Table 2, PLA requires industrial composting conditions and cannot achieve rapid degradation under natural conditions. Additionally, the backend processing facilities of composting plants are not widespread in our country, where waste management practices mainly involve landfilling and incineration, without achieving effective circularity. In contrast, PHA can be decomposed by microorganisms in nearly all environments, including composting, soil, and seawater. The by-products of this decomposition are primarily water and carbon-based, thus avoiding environmental pollution. This performance stands as a substantial advantage of PHA over PLA[5].

Table 2. Comparison of PLA and PHA degradation methods[5]

Materials	Degradation mode and rate
PLA	Industrial composting conditions (above 58 °C, aerobic flora): 84% degradation rate in 58 days
	Anaerobic composting conditions (58 °C, 60% humidity): 60% degradation rate in 30 days
PHA	In soil environment (35 °C): 35% degradation rate in 60 days (it can be degraded in nature environment, and the degradation time is controllable)

PHA's Gas Barrier Property is Superior to PLA. Natural or synthetic biodegradable high molecular weight materials often exhibit high water vapor permeability, which is unfavorable for food preservation. In contrast, PHA boasts excellent gas barrier properties, making it suitable for longer-term fresh food preservation packaging. PHA's Flexibility Compared to PLA. PHA demonstrates higher flexibility compared to PLA. Given the diverse range of PHA monomer structures, there can be substantial variations in performance. By adjusting monomer structures and ratios, polymer properties can be tailored, leading to higher flexibility in applications.

PHA's Current and Projected Production Capacity Compared to PLA. Both PHA's existing and projected production capacities are relatively small compared to PLA. This primarily results from the immature state of production technologies for these types of biodegradable plastics, leading to high production costs and limited market recognition. At present, PHA struggles to compete with PLA as a replacement for conventional plastics. However, PHA's outstanding material properties, biodegradability, and carbon reduction performance have spurred rapid market demand growth. According to data from the European Bioplastic Conference, in 2020, PHA accounted for less than 2% of global bioplastics production capacity. However, by 2025, the proportion of PHA bioplastics is projected to rise to 11.5%, approaching the usage levels of PBAT and PLA. Estimated future global demand for PHA over the next 20 years will reach 10 million tons, creating a market valued at around 40 billion Dollars, and the share is anticipated to increase from 2% to 11.5% over the next 5 years.

PHA's Potential Compared to PLA. In comparison to PLA, PHA has significant room for price reduction and adjustable performance. Presently, PHA is in a state of undersupply in the market, priced at around 8 times that of traditional petroleum-based plastics. After achieving large-scale production, its price might become competitive with PLA. As market participants increase, the likelihood of a decrease in PHA's price as a commodity is high. It is foreseeable that with the influx of substantial capital, PHA production capacity will further increase, potentially addressing concerns about raw material prices. In the medium to long term, reducing the complexity and manufacturing cost of PHA production will contribute to a golden era of development for the PHA industry.

3.4. Production of PHA from industrial wastes

50% of the entire production cost of PHA is determined by the cost of raw materials, so using waste as the starting material for PHA biosynthesis to form a cost-effective biopolyester production system is not only conducive to solving the problem of high PHA raw material cost, but also to overcome the waste disposal problem[6].

3.4.1. Surplus whey from the dairy industry

The annual global production of whey is about 1. 35 × 108t, lactose is the main carbohydrate in whey, which can be used as a growth substrate and raw material for many biotechnology products, and the cost of lactose is only 1/4 of glucose[7]. The main advantage of using whey to produce PHA is that the source of raw materials is relatively stable, but the disadvantage is that there are few strains that can directly convert whey into PHA, and the strains need to be genetically engineered. The results of PHB production by recombinant Escherichia coli in whey have been reported in the literature. Using whey as carbon source, recombinant Escherichia coli was cultured by fed-batch fermentation with PHB concentration of 69mg /L and yield of 1. 4 g / L/ h [8]. Ahn et al. used pH value to monitor and replenish the feed in a steady state to maintain a high concentration of whey (280 g / L) in the culture system, and the final dry weight and PHB yield of the bacteria were 120 g / L and 96 g / L, respectively[9]. Nikel et al. used whey and corn pulp as carbon and nitrogen sources to obtain 2. PHB yield of 13 g / (L· h)[10].

3.4.2. Waste from biofuel sources

With the rapid increase in biofuel production, the production of by-product glycerol liquid phase (70% glycerol) has also increased. Using this product as raw material to produce other compounds can not only improve the economy of biodiesel production, but also have ecological rationality. Since glycerol can directly participate in glucose metabolism and fat metabolism, many microbial strains can produce PHA polyester and lactic acid using liquid glycerol as substrate without going through purification steps such as degreasing or demethanol[11]. However, when glycerin or ethylene glycol is added, these substances terminate the chain extension by covalently linking the carboxyl end of the polyester, reducing the molecular weight of the PHA[12]. In addition, the residual methanol in liquid glycerol may also affect the growth of the strain.

4. Analysis Report on the Transformation of Singapore's Food Packaging Industry

4.1. Industry Background

The food packaging industry is a crucial component of the food sector, playing a vital role in ensuring food safety, extending product shelf life, and enhancing product image. According to the report, the market size of Singapore's food packaging industry was $1 billion in 2019 and is projected to reach $1.5 billion by 2025. Data from Singapore's environmental department indicates that approximately 137,000 tons of plastics are used for food packaging annually, with a significant portion being single-use plastic products. This has led to a severe plastic pollution problem, resulting in significant impacts on the environment and ecosystems.

For polyhydroxyalkanoate (PHA), a biodegradable material with environmentally friendly attributes, there is a clear role to play. PHA is biodegradable plastic that can be decomposed by microorganisms in natural environments, unlike traditional plastics that persist indefinitely. Moreover, PHA can be produced using agricultural waste, food scraps, and other organic materials as feedstock. This production method reduces reliance on fossil fuels, lowers carbon emissions, and has a reduced environmental impact. As a result, PHA serves as an eco-friendly alternative that can address plastic pollution issues.

PHA's applications are as diverse as polyethylene (PE). Apart from food packaging, PHA materials can be used in the manufacturing of disposable cutlery, bags, bottles, and other plastic products. Beyond Singapore, an increasing number of countries and regions worldwide are focusing on the use of biodegradable materials, driving the development of the PHA materials market. This presents broader market opportunities for PHA material producers in Singapore.

4.2. Market Analysis

Based on market research data, the global biodegradable materials market is projected to grow from $10.3 billion in 2019 to $16.2 billion by 2025, with a compound annual growth rate of 8.4%. Focusing on Singapore, the sales of products using PHA materials in the food packaging industry have demonstrated steady growth over the past few years. Singapore government statistics show that in 2017, 2018, and 2019, the sales of products using PHA materials in the food packaging industry were $100 million, $150 million, and $200 million, respectively, accounting for 10%, 12%, and 15% of the total market size. According to the report, the projected compound annual growth rate of Singapore's food packaging industry is 5.2%, expected to reach $1.5 billion by 2025. Based on preliminary data analysis, the sales of products using PHA materials are expected to grow to $300 million, accounting for 20% of the total market size.

4.3. Feasibility Analysis (Reasons for Transformation)

Consumer Level: Offline survey data shows that approximately 80% of consumers are more attentive to biodegradable food packaging materials and favor food packaging that uses biodegradable materials. They consider environmentally friendly packaging materials when making purchasing decisions. Around 70% of consumers express concern about the environmental friendliness of food packaging and are willing to pay a higher price for products with environmentally friendly packaging materials. This data indicates an increase in consumer recognition and acceptance of eco-friendly materials.

Environmental Level: According to data from Singapore's Sustainable Development Board, effectively replacing PE with PHA in the food packaging industry could lead to a reduction of approximately 30% in carbon emissions, which has a positive impact on mitigating climate change.

Policy Level: The Singaporean government encourages the use of biodegradable materials and has introduced a series of policies and incentives, including reducing plastic waste and promoting the production and application of biodegradable materials. Analysis suggests that due to Singapore's status as a tropical island nation, its economy, well-being, and infrastructure heavily depend on the islands. Therefore, compared to landlocked countries, Singapore is highly sensitive to greenhouse gas emissions and rising sea levels in various aspects, such as economy, politics, and livelihoods. The government is more proactive in promoting environmentally friendly materials.

Industry Level: With technological advancements, PHA material production technology and costs are expected to improve gradually. According to a report from Harvard University, it is projected that by 2025, the production cost of PHA materials may decrease by 20 % - 30 %.

4.4. Financial Analysis

(1) Cost Analysis

The price of PHA is approximately 3 to 10 times that of regular polyethylene and polypropylene, which becomes a significant factor constraining the commercial development of PHA (Table 3). The high production cost of PHA primarily stems from elevated raw material costs, high equipment operating expenses, and substantial product purification costs[13]. Drawing a comparison with Chinese enterprises, the average market price of PHA is $5,500 per ton. If the annual production is 2,197.25 tons, requiring 83 units of equipment, the investment needed would be $4.8597 million in fixed assets and $1.3298 million in current assets[14].

Table 3. Key Economic Indicators of PHA Establishment[15]

Projects	Units	Numerical Value
Investment Intensity	$10,000 Per Acre	24.13103
Gross Investment	$10,000	621.9324
Fixed Investments	$10,000	488.4124
Working Fund	$10,000	133.52
Income	$10,000	1212.276
Gross Cost	$10,000	921.5131
Total Profit	$10,000	290.7628
Retained Profits	$10,000	218.0717
ROI (Return on Investment)		35.06%
Payback Time	Years	4.35
Quantity Of Facility	Units	83
Annual Electricity Consumption	Kilowatt-Hour	1200962.16
Annual Water Consumption	Stere	6567.61
Total Energy Consumption	Ton of Standard Coal	148.16
Fractional Energy Saving		23.69%
Amount of Energy Saving	Ton of Standard Coal	39.38
Number of Staff	People	196

(2) Market Forecast

Currently, Singapore has a total population of around 5.64 million[16]. It is projected that each person consumes about 10 food packaging bags per day (this includes packaging bags generated from fresh food transportation consumed during dining out)[17]. This results in Singapore consuming approximately 20.9 billion packaging bags annually[18]. Around 70% of consumers express concern about the environmental friendliness of food packaging (Figure 5). They are willing to pay higher prices for products packaged with environmentally friendly materials.

Figure 5. Specific Application Areas of PHA Downstream

(3) Revenue Forecast

a. Profitability Analysis: PHA is an excellent biodegradable material, and in environmentally sensitive Singapore, it has a significant developmental advantage. In developed countries with a high focus on the environment, PHA's substitution for traditional materials is highly accepted by the masses and offers broad application prospects, leading to optimistic product profitability[19].

b. Operational Capability Analysis: The traditional packaging material sector has a well-established supply chain and ample cash flow. Material research and development teams can promote PHA materials to traditional packaging enterprises, reducing the difficulty of market expansion and fostering win-win collaborations[20].

4.5. Transformation Challenges

a. Technical Challenges: The production technology for PHA materials is relatively complex, resulting in higher production costs, about 2-3 times that of traditional plastics. Further research and improvements are needed to enhance production efficiency and cost reduction[21].

b. Market Acceptance: The application of PHA materials is relatively new, and market acceptance is limited. According to market research data, 70% of consumers are willing to pay a higher price for products using environmentally friendly materials, but only 2% of consumers are familiar with PHA materials.

c. Market Monopoly: Traditional plastic packaging materials dominate the food packaging industry, and large enterprises possess economies of scale and market shares, posing certain constraints on the application of PHA materials[22].

4.6. Transformation Strategies

a. Technology Research and Development: Increase investment in PHA material research and development to enhance production processes, efficiency, and cost reduction. According to projections, by 2025, the production cost of PHA materials is expected to decrease to 1.5 times that of traditional plastics[23].

b. Market Promotion: Strengthen the promotion and awareness of PHA materials among consumers. According to market research data, with active promotional efforts, consumer recognition of biodegradable materials is expected to increase beyond the current 70%.

c. Collaboration for Mutual Benefits: In addition to the aforementioned Chinese companies investing in PHA industrialization research, universities around the world have also made contributions in related fields. For instance, PHA (polyhydroxyalkanoate) is a biodegradable plastic material that has garnered widespread attention and research globally[24].

The following are universities with significant influence in researching PHA materials:

The Laboratory for Sustainable Plastics at Stanford University focuses on PHA synthesis, biodegradation, and applications[25]; The Institute of Biology II and Faculty of Engineering at the University of Freiburg conducts extensive research in PHA, including production, synthesis, and applications[26]; The Microbiology and Biochemistry group at Wageningen University & Research in the Netherlands conducts research on PHA production, microbial strain screening, and modifications; The Institute for Integrated Cell-Material Sciences at Kyoto University in Japan conducts research on PHA material synthesis, functionalization, and applications; Nanyang Technological University in Singapore's School of Materials Science and Engineering conducts various research on PHA materials, including synthesis, biodegradability, and applications.

Currently, Nanyang Technological University, along with globally renowned universities like Harvard, has initiated research on environmentally friendly packaging materials and has achieved initial results[27]. Therefore, considering Singapore's strong academic capabilities and the limited foundation of its industrial base, it is crucial to strengthen industry-academia collaboration, promote technological innovation and application of PHA materials, establish a complete industrial chain, and achieve resource sharing and mutual benefits.

5. Simulation Analysis of Complete Replacement of LDPE with PHA in Singapore

In this section, we conducted a simulation analysis of the complete replacement of LDPE with PHA using 2021 Singapore import data as a reference sample. We explored key issues related to overall replacement costs, packaging cost increases, and adjustments in profit margins and selling prices during the substitution process.

5.1. Overall Replacement Costs

Began by comparing the prices of PHA and LDPE. According to reference data, the price of PHA is $5.5 per kilogram[27][28][29], while the average import price of LDPE, calculated based on Singapore import data from 2019 to 2021, is $1.296 per kilogram. Through simulation, we calculated that the total amount required for a complete replacement of LDPE with PHA is $4,580,845,137, which is equivalent to 4.04 times the market size of imported LDPE. This outcome reveals that substituting PHA for LDPE would significantly increase import costs.

5.2. Increase in Packaging Costs

We considered variations in packaging costs within the analysis. Based on simulation calculations, packaging costs would increase by 4.04 times. This implies that under the scenario of complete replacement of LDPE with PHA, there would be a noticeable increase in packaging costs.

5.3. Profit Margin and Selling Price Adjustments

We further examined the cost structure and profit margins of retail products. Given that packaging costs typically account for about 10% of total costs[31], and retail product gross profit margins range from 8-25% (https://www.allianceexperts.com/zh-hans/margin-reseller-distributor/), we used the example of a $2 loaf of bread to calculate actual costs and packaging actual costs. Subsequently, we simulated the adjustments in selling prices following the transition to PHA replacing LDPE[32].

Specifically, if businesses decide to maintain the existing profit unchanged, they will need to raise the actual selling price by $0.456 (22.8% increase) to address the cost increase resulting from PHA replacing LDPE. Conversely, if businesses opt to maintain the existing profit margin, they will need to raise the actual selling price by $0.608 (30.4% increase) to balance the impact of the cost increase.

5.4. Conclusion and Outlook

Considering our analysis, we concluded that in the case of a complete replacement of LDPE with PHA, there would be an increase in overall replacement costs, a significant rise in packaging costs, and adjustments in retail product selling prices. It's important to note that these calculations are based on a set of assumptions and parameters, and actual circumstances could be influenced by various factors. Therefore, our calculation results offer a reference point, but practical business decisions require comprehensive consideration of factors such as market conditions, competitive dynamics, and consumer responses.

In future research, further exploration of the business impact of PHA substituting LDPE under different market conditions, as well as strategies for balancing cost and profit challenges in practical operations, will be valuable. This will contribute to a more comprehensive understanding of the impact of PHA replacing LDPE on the business ecosystem.

5.5. Actual Estimation Process

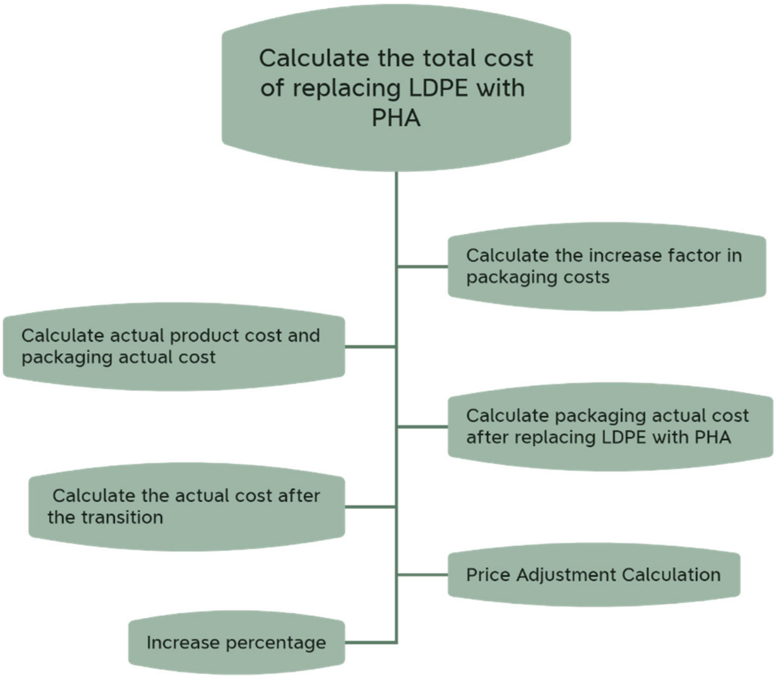

Figure 6. Actual Estimation Process

(1) Total Cost Calculation for Replacing LDPE with PHA

LDPE Market Size = $689,662,262

LDPE Import Quantity = 481,103,202 kg

LDPE Unit Import Price = $1.296247061 per kg

PHA Unit Price = $5.5 per kg

Total Amount for PHA to Replace LDPE = LDPE Import Quantity * PHA Unit Price Total Amount for PHA to Replace LDPE = 481,103,202 kg * $5.5/kg Total Amount for PHA to Replace LDPE = $2,645,567,611

Multiplier of Total Amount for PHA to Replace LDPE relative to LDPE Imports = Total Amount for PHA to Replace LDPE / LDPE Market Size Multiplier of Total Amount for PHA to Replace LDPE relative to LDPE Imports = $2,645,567,611 / $689,662,262 ≈ 4.04

(2) Calculation of Increase Factor in Packaging Costs

Increase Factor in Packaging Costs = Multiplier of Total Amount for PHA to Replace LDPE relative to LDPE Imports = 4.04

(3) Calculation of Actual Product Cost and Packaging Actual Cost

Assuming a gross margin of 25%:

Actual Product Cost = Product Selling Price * (1 - Gross Margin)

Packaging Actual Cost = Actual Product Cost * Proportion of Packaging Costs

Actual Product Cost = $2 * (1 - 0.25) = $1.5 Packaging Actual Cost = $1.5 * 0.10 = $0.15

(4) Calculation of Packaging Actual Cost after Replacing LDPE with PHA

Packaging Actual Cost after Replacing LDPE with PHA = Packaging Actual Cost * Increase Factor in Packaging Costs Packaging Actual Cost after Replacing LDPE with PHA = $0.15 * 4.04 = $0.606

(5) Calculation of Actual Cost after the Transition

Actual Cost after Transition = Packaging Actual Cost after Replacing LDPE with PHA + Actual Product Cost - Packaging Actual Cost Actual Cost after Transition = $0.606 + $1.5 - $0.15 = $1.956

(6) Price Adjustment Calculation

To maintain the original profit:

Actual Cost Increase = Packaging Actual Cost after Replacing LDPE with PHA - Packaging Actual Cost

Actual Cost Increase = $0.606 - $0.15 = $0.456

To maintain the original profit margin:

Actual Cost Increase = Actual Cost after Transition / Gross Margin - Actual Product Cost

Actual Cost Increase = $1.956 / 0.25 - $1.5 = $0.608

(7) Increase Percentage Calculation

To maintain the original profit:

Increase Percentage = Actual Cost Increase / Original Product Price

Increase Percentage = $0.456 / $2 * 100% = 22.8%

To maintain the original profit margin:

Increase Percentage = Actual Cost Increase / Original Product Price

Increase Percentage = $0.608 / $2 * 100% = 30.4%

These calculations are based on conservative estimates, and actual price increases may vary due to factors such as retail product costs, packaging costs, gross margin, PHA material prices, etc. The provided results are intended for reference purposes (Table 4).

Table 4. Simulation calculation flow table

No.	Calculation Description	Result
(1)	Calculate the total cost of	
	LDPE Market Size	\$689,662,262
	LDPE Import Quantity	481,103,202 kg
	LDPE Unit Import Price	\$1.296247061/kg
	PHA Unit Price	\$5.5/kg
	Total Amount for PHA to	\$2,645,567,611
	Multiplier of Total Amount for	4.04 times
(2)	Calculate the increase factor in	4.04 times
(3)	Calculate actual product cost	
	Actual Product Cost	\$1.5
	Packaging Actual Cost	\$0.15
(4)	Calculate packaging actual cost	\$0.606
(5)	Calculate the actual cost after	\$1.956
(6)	Price Adjustment Calculation:	
	To maintain the original profit,	\$0.456
	To maintain the original profit	\$0.608
(7)	Increase percentage:	
	To maintain the original profit,	22.8%
	To maintain the original profit	30.4%

6. Conclusion

Singapore presents a vast scale in plastic usage, with polyethylene (PE) being one of the main plastic types. However, polyhydroxyalkanoates (PHA), as a biodegradable plastic, demonstrate extensive application prospects. PHA can not only replace PE in many traditional plastic applications but also possesses biodegradability, offering potential solutions to plastic pollution.

Commercial analysis reveals a positive growth trajectory for the PHA industry. Its biodegradability and environmentally friendly characteristics have captured the attention of consumers and businesses alike. In the context of the plastic market's continuous search for sustainable alternatives, PHA holds potential for transformation and value addition. From a business perspective, the continual innovation and cost reduction of PHA production technology are poised to facilitate large-scale commercial production, further expanding its application domains.

A comprehensive analysis reveals that in the scenario of PHA completely replacing LDPE, not only does the overall substitution cost increase, but also packaging costs for goods experience a significant rise, necessitating corresponding adjustments in retail prices. These calculations are based on a range of assumptions and parameters, with actual outcomes susceptible to various influencing factors. Therefore, these computed results offer a reference point, but real business decisions require a comprehensive consideration of factors such as market conditions, competitive dynamics, and consumer responses. Future research can further delve into the commercial implications of PHA replacing LDPE in diverse market settings, along with strategies for effectively balancing costs and profits in practical operations. This endeavor will contribute to a more comprehensive understanding of the impact of PHA replacing LDPE on the business ecosystem.

7. Competing Interests

All authors declare no Competing Financial or Non-Financial Interests.

8. Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

9. Funding Declaration

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